

# Time delay between images of the lensed quasar UM673

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## ABSTRACT

**Aims.** We study brightness variations in the double lensed quasar UM673 (Q0142-100) with the aim of measuring the time delay between its two images.

**Methods.** In the paper we combine our previously published observational data of UM673 obtained during the 2003 – 2005 seasons at the Maidanak Observatory with archival and recently observed Maidanak and CTIO UM673 data. We analyze the V, R and I-band light curves of the A and B images of UM673, which cover ten observational seasons from August 2001 to November 2010. We also analyze the time evolution of the difference in magnitudes between images A and B of UM673 over more than ten years.

**Results.** We find that the quasar exhibits both short-term (with amplitude of  $\sim 0.1$  mag in the R band) and high-amplitude ( $\sim 0.3$  mag) long-term variability on timescales of about several months and several years, respectively. These brightness variations are used to constrain the time delay between the images of UM673. From cross-correlation analysis of the A and B quasar light curves and error analysis we measure the mean time delay and its error of  $89 \pm 11$  days. Given the input time delay of 88 days, the most probable value of the delay that can be recovered from light curves with the same statistical properties as the observed R-band light curves of UM673 is  $95^{+5}_{-16}$  days (68 and 95 % confidence intervals). Analysis of the  $V - I$  color variations and V, R and I-band magnitude differences of the quasar images does not show clear evidence of the microlensing variations between 1998 and 2010.

**Key words.** Gravitational lensing: strong – Methods: data analysis – (Galaxies:) quasars: individual: UM673

## 1. Introduction

Multiple images of lensed quasars show change in their brightness over time. There are two main reasons for these brightness variations. One is that the quasar itself, as a variable source, changes in brightness with time. Corresponding brightness variations are observed in the light curves of all quasar images, but not simultaneously. Changes in brightness in one image follow or lead the brightness changes in the others with a certain time lag (time delay). The time delay between these brightness variations in the quasar images is a combination of delays that arise due to geometrical differences between the light paths (and thus light travel times) for each quasar image and the difference in the gravitational potential of the lensing galaxy between image positions. The geometrical term is related to the Hubble constant through the angular diameter distances (see Schneider et al. 1992). This relation gives us a method for estimation of the Hubble constant independently of the distance ladder (Refsdal 1964). The potential term is determined by the mass distribution in the lens. Thus the mass distribution of distant galaxies can be studied using the time delays as one of the observational constraints (see, e.g., Kochanek 2002).

The passage of individual stars in the lensing galaxy near the light paths of quasar images will also cause variations in bright-

ness known as microlensing (Chang & Refsdal 1979). These brightness variations are not similar in each of the quasar images. The probability for microlensing depends on the density of stars at positions of the images. Normally we would expect both microlensing variations and variations intrinsic to the quasar to be present in the light curves of the quasar images. Accurate measurement of the time delay between the images ensures that variations due to microlensing can be separated from the variations intrinsic to the quasar (see Paraficz et al. 2006). However, time delay measurement itself is often not a simple and straightforward task. Successful measurement of the delay requires a combination of several conditions, such as a change in the brightness of the quasar during observations, good sampling and observational time spans, and minimal contamination of the quasar's intrinsic variations by variations due to microlensing.

In this study we analyze brightness variations in images of the lensed system UM673 (Q0142-100) discovered by MacAlpine & Feldman (1982). The system consists of a distant quasar at redshift  $z_q = 2.719$  (Surdej et al. 1987, 1988) gravitationally lensed by an elliptical galaxy at redshift  $z_l = 0.49$  (Surdej et al. 1988; Smette et al. 1992; Eigenbrod et al. 2007) into A and B images with the image separation of  $2''.2$ .

UM673 has been extensively observed since its discovery (Daulie et al. 1993; Sinachopoulos et al. 2001). However, earlier studies measured only relative or integral photometry of the two

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of UM673 images, so the detected brightness variations could be explained by both intrinsic quasar variability and microlensing.

The first V and i-band light curves for each of the A and B images of UM673 were presented in Nakos et al. (2005). The observations showed both quasar components to be variable on timescales ranging from several months to years. During the first season of observations, Nakos et al. (2005) detected a short-term event lasting for 120 days in both A and B images. It had an amplitude of about 0.08 mag in the V band. The overall brightness changes detected in one year of observations were 0.14 and 0.08 mag in the V and Gunn i bands, respectively. Nakos et al. (2005) did not measure the time delay between the images. After shifting the light curve of image B relative to that of image A they found that the observed brightness changes of these images did not match each other. Thus, they concluded that either the time delay between the images was longer than 150 days (150 days was the duration between two consecutive V-band observations of UM673 in the 1999 and 2001 seasons) or the brightness variations were contaminated by microlensing. Their analysis of the  $V - i$  color indices of images A and B showed that the part of the variations in the brighter A image might be connected to microlensing by the stars in the lensing galaxy. It was found that image A became bluer as its brightness increased as expected during microlensing (Wambsganss & Paczinski 1991). The brightness and color variations in image B were puzzling and could not be interpreted unambiguously. Analysis of the UM673A&B emission line-to-continuum ratios from September 2002 showed them to be the same in both images, as it would be expected in the absence of microlensing (Wisotski et al. 2004).

We have been conducting monitoring observations of several gravitationally lensed systems with the aim of measuring the lensing time delays, and to study microlensing variability (see Koptelova et al. 2005, 2006, 2007; Ullán et al. 2006; Goicoechea et al. 2006, 2008; Shalyapin et al. 2008, 2009). UM673 is one of our targets. In our first paper (Koptelova et al. 2010; Paper I) we presented an analysis of observations of the UM673 system obtained with the 1.5-m telescope of the Maidanak Observatory (see also Koptelova et al. 2008). Observations were made in the V, R and I bands in the 2003, 2004 and 2005 observational seasons. The two UM673 components brightened during the first season of observations and then gradually faded until the end of 2005. We interpreted the similar photometric behavior (brightening and fading) of the A and B images as due to variability intrinsic to the quasar. Given this assumption, the cross-correlation analysis led to the time delay between images A and B images of about 150 days (image A is leading).

Unfortunately, the data presented in Paper I did not allow for a detailed interpretation of the observed brightness variations. In the current work we present new photometry and time delay analysis of the longer observational records collected between August 2001 and November 2010. The details of the monitoring program and the observational data are presented in Sects. 2 and 3, respectively. Based on new observations and analysis of the observed brightness variations we measure a revised time delay between images A and B. The analysis of the brightness variations in the system UM673 and the time delay measurements are presented in Sects. 4 and 5. A discussion is given in Sect. 6.

## 2. Observations

In the study we use monitoring observations of UM673 obtained during different observational seasons at two sites. The majority of the observational data were collected during a quasar monitoring program carried out by the Maidanak GLQ collaboration

(see Dudinov et al. 2000). Images in the Bessel V, R and I bands were obtained with the 1.5-m AZT-22 telescope of the Maidanak Observatory (Central Asia, Uzbekistan) during the 1998 – 2010 observational seasons. A considerable part of these observations, the 2003 – 2005 data, have been presented in Koptelova et al. (2008) and Paper I. The V, R and I-band observations of the lensed system were also made between July 28, 2008 and January 18, 2010 using the 1.3-m SMARTS telescope at CTIO, Chile (as a part of the ToO observations carried out by National Central University, Taiwan). UM673 was usually observed from August until December, or sometimes January, when it was well visible at both sites. A summary of the observational data acquired between 1998 and 2010 are given in Table 1.

The Maidanak data were obtained with different CCD cameras installed at the 1.5-m telescope. During the 1998 observational season images were obtained with the TI 800 x 800 Pitt and Pictor-416 CCD cameras with pixel scales of 0.13 and 0.16 arcsec pixel<sup>-1</sup>, respectively. The 1999 images were obtained with the ST-7 760 x 510 pixel CCD provided by the Maidanak Foundation (see Dudinov et al. 2000). The field of view (FOV) of the images taken with these three CCD cameras was small so images did not include any bright stars in the vicinity of UM673, which are useful for performing differential photometry of the UM673 A and B quasar images. Between August 2001 and August 2006 images were obtained with the 2000 x 800 pixel SITE-005 CCD camera manufactured in the laboratory of Copenhagen University. The images taken in long-focus and short-focus modes have pixel scales of 0.135 and 0.268 arcsec pixel<sup>-1</sup>, respectively. The most recent observational data were obtained with a new 4096 x 4096 SNUCAM camera provided by Seoul University. The images taken with this CCD camera have pixel scale of 0.266 arcsec pixel<sup>-1</sup> and FOV of 18'1 x 18'1. The characteristics and performance of SNUCAM on the 1.5-m telescope are discussed in detail in Im et al. 2010. The 1.3-m SMARTS telescope obtained images using the dual-channel optical/near-infrared CCD camera ANDICAM which has an optical FOV of 6'3 x 6'3 (0.369 arcsec pixel<sup>-1</sup>). On each observational night images were taken in a series of 2 – 8 frames in all three V, R and I bands.

## 3. UM673 A and B light curves

The V, R and I-band photometry of UM673 from August 2001 to November 2010 is now discussed. In the current work we revisit photometry of UM673 between the 2003 – 2005 observational seasons presented in Koptelova et al. (2008) and Paper I (magnitudes of the A and B images of UM673 for this period are given in Table 2 of Koptelova et al. 2008), and perform photometry of the 2001 and 2006 – 2010 data. The photometry method we use is the PSF fitting method and it has been described in our first paper. In the current analysis we improve the accuracy of photometry in the following ways. First, we find that performance of the PSF fitting method is poor when applied to the individual frames of UM673. The fainter components of UM673 has low signal-to-noise ratio, especially in the new 2006 – 2010 data when the quasar was faint. For example, the signal to noise ratio of the A and B images of UM673 in the 2006 R-band data is estimated to be about 200 and 70, respectively. The low performance results in high level of statistical and correlated errors. We find that these errors are more severe for the 2006 – 2010 data and significantly affect the cross-correlation analysis of the 2006 – 2010 light curves producing spurious peaks at short time lags. Therefore, in order to minimize the errors, we apply the PSF fitting method to the combined frames of UM673. The combined

**Table 1.** Summary of the UM673 observational data collected during the 1998 – 2010 seasons.

Telescope	CCD camera	Bands / Exposures	Period	Number of nights
1.5-m AZT-22	Pitt CCD	V (240 s), R(240 s), I(240 s)	Nov 1998	9
	Pictor-416 CCD	V (180 s), R(180 s), I(180 s)	Dec 1998	5
	ST-7	R (180 s)	Sep 1999	3
	SITe-005	V (210 s), R (180 s), I (150 s)	Aug 2001 – Jan 2006	134
	SNUCAM	V (200 s), R (200 s), I (200 s)	Aug 2006 – Nov 2010	92
1.3-m SMARTS	ANDICAM	V(200 s), R (200 s), I (200 s)	Aug 2008 – Jan 2010	30

frames are a sum of two or three individual frames with similar seeing taken at the same observational night. Usually we sum up three sequential frames from the same night series. For small fraction of nights, when the system was observed only two times, we sum up two frames of UM673. This allows us to enhance the signal-to-noise ratio of the images by a factor of  $\sqrt{3}$  or  $\sqrt{2}$ . Second, in the current analysis we choose several isolated stars around UM673 to construct the PSF model. The shape of the PSF can vary over image plane as a result of optical aberrations in the telescope and camera system. The aberrations will distort the PSF shape from the center outwards. We estimate that this effect is more severe for the new 2006 – 2010 Maidanak data taken with the large area 4096 x 4096 pixel SNUCAM CCD. UM673 is usually not in the center of the SNUCAM frames. In this case, the PSF constructed from several nearby stars is a better representation of the PSF shape at the location of UM673 on the image frame. The PSF was constructed using the bright star north-east of UM673, labeled as star 1 (see Fig. 1 in Paper I), and stars 1 and 3 from the catalog of secondary standard stars around lensed quasars (see Nakos et al. 2003). In this way, the photometric analysis was conducted in the same manner for the whole data set. The measured fluxes were calibrated relative to star 1 introduced in Paper I. The magnitudes of star 1 in the V, R and I bands are  $m_V = 14.653 \pm 0.008$ ,  $m_R = 14.278 \pm 0.008$  and  $m_I = 13.954 \pm 0.009$  mag, respectively.

There might be a contribution of the lensing galaxy into the flux of the closest image B. It is estimated to be negligible in the V band ( $m_{\text{gal}}^V = 20.81$  mag (Lehár et al. 2000)). The galaxy contribution in the R and I-band fluxes of image B are measured to be 0.069 and 0.126 mag, respectively (see Koptelova et al. 2008).

The resulting Maidanak and CTIO R-band light curves of the A and B quasar images are shown in Fig. 1. The filled circles indicate the Maidanak data points for images A and B, respectively. The triangles and stars indicate the CTIO data points obtained during the 2008 – 2010 seasons for images A and B, respectively. The V and I-band light curves presented in Figs. 2 and 3 are available in the electronic version of the paper. Transmission properties of the CTIO filters are slightly different from the Bessel filters used in the Maidanak observations<sup>1</sup>. We measure that magnitude differences between star 3 and bright star 1 in the Maidanak images are 2.850, 2.878 and 2.892 mag in the V, R and I bands, respectively. The corresponding differences in the CTIO images are 2.916, 2.942 and 2.977 mag in the V, R and I bands, respectively. The CTIO light curves are matched to the Maidanak light curves taking into account these differences in the relative magnitudes of stars 1 and 3 in the different bands. The photometric errors of the individual measurements were estimated as standard deviations of the mean values

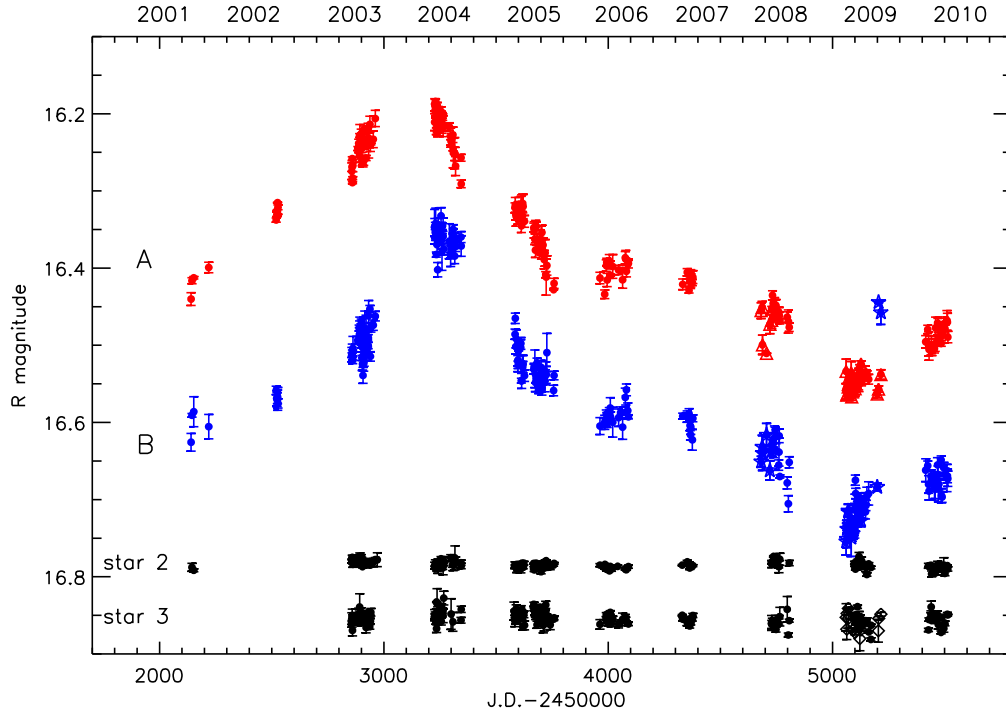
of several measurements made on each observational night. The mean standard errors of the photometry in the R band are estimated to be  $\bar{\sigma}_A = 0.007$  and  $\bar{\sigma}_B = 0.010$  mag for images A and B, respectively. Fig. 1 also shows the light curves for reference stars 2 and 3 in the field of view of UM673. Stars are labeled as in our first paper (see Fig. 1 in Paper I). The fluxes of these two stars were measured relative to calibration star 1. From our data, the R-band magnitude of star 2 is  $m_R = 16.246 \pm 0.008$  mag. Photometry of other nearby stars in the field of UM673, including star 3 ( $m_R = 17.196 \pm 0.014$ ), was presented in Nakos et al. (2003). The field of view of the images taken with the 1.3-m SMARTS telescope is smaller and does not include star 2 or some other bright stars seen in the Maidanak images. Therefore, for the CTIO images we plot the relative photometry of star 3 and bright star 1 (indicated by the open rhomboids in Fig. 1).

As can be seen in Fig. 1, the global brightness changes of both components of UM673 are similar over the course of our observations. Along with the long-term brightness changes which take years, we can detect short-term brightness variations on timescales of several months. These variations on different timescales probably have a different origin. The global long-term behavior of the light curves with the largest brightness changes (more than 0.3 mag in the R band) might be connected with the formation and evolution of the accretion disk (e.g., Lyuty 2006, Arévalo et al. 2009). In these long-term brightness variations we can distinguish a global maximum and minimum observed in both light curves in 2004 and in 2009, respectively. The short-term brightness variations might be due to reprocessing of the X-ray flares by the accretion disk (see Krolik et al. 1991). Short-term brightness variations of the UM673 images on timescales of several months have been previously detected by Nakos et al. (2005). Between January 2 and 18, 2010 we detect fast high-amplitude variability event in image B of UM673. The amplitude of this event is several times higher than it is usually observed on similar timescales within the observational seasons. If this brightness variation is a result of quasar variability then similar variation has to be seen first in image A. However, we do not detect similar event in the image A light curves during the same observational season. Although there is no other variation like the image B event in the A and B light curves, it might not be unique for the lensed system. Analysis of the flux ratios between image A and B in 1998 shows another evidence of short-term variations of comparable amplitude. This event is discussed later in Sect. 5. In the next section, we perform cross-correlation analysis of the A and B light curves to measure the time delay between the quasar images.

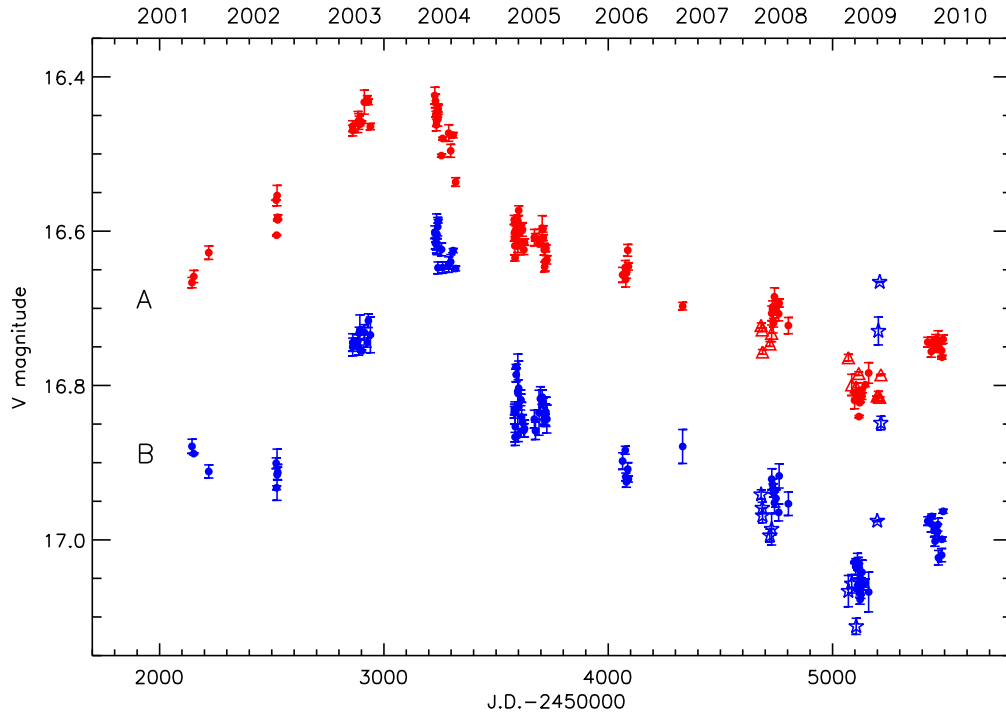
#### 4. Intrinsic quasar variability and time delay analysis

Earlier estimate of the time delay between the A and B images of UM673 was made based on slow long-term brightness

<sup>1</sup> Transmission curves of the CTIO filters in comparison with the Bessel filters can be found at <http://www.ctio.noao.edu/telescopes/50/1-3m.html>



**Fig. 1.** R-band light curves of the A and B images of UM673 from August 2001 to November 2010. For better representation, the light curve of image B is shifted by -1.87 mag. The light curves of reference stars 2 and 3 are shown at the bottom.

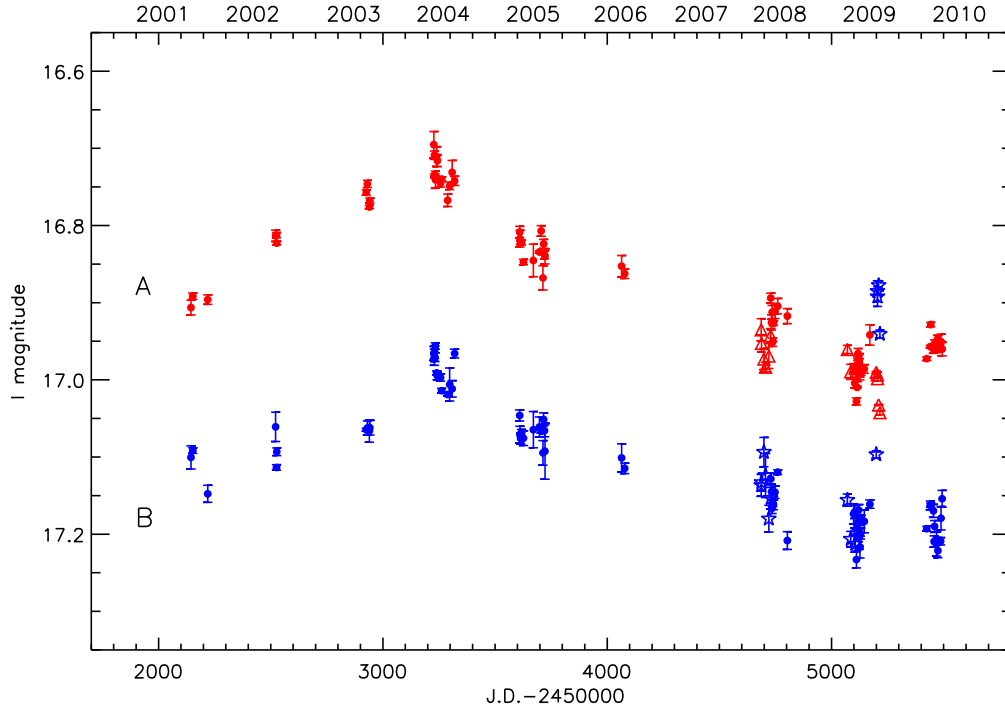


**Fig. 2.** V-band light curves of the A and B images of UM673 from August 2001 to November 2010. The light curve of image B is shifted by -1.95 mag.

changes observed between the 2003 – 2005 seasons. Analysis of the better-sampled R-band light curves gave a time delay and conservative error of  $150^{+7}_{-18} +^{42}_{-36}$  days (confidence levels of 68 and 95 %) (see Paper I). The estimated delay of 150 days is comparable to one season of observations of the lensed system at the Maidanak Observatory. The light curves of the A and B

quasar images shifted by this delay did not overlap each other. This made it difficult to verify the obtained result.

The observations of UM673 also show noticeable brightness changes within each observational season. These short-term brightness variations observed in the quasar images have not been considered carefully in Paper I given the assumption



**Fig. 3.** I-band light curves of the A and B images of UM673 from August 2001 to November 2010. The light curve of image B is shifted by -1.62 mag.

that the quasar brightness does not change significantly on short timescales. Moreover, there are more features in the global behavior of the light curves than it was available before. The quasar seems to reach the minimum of its brightness in 2009 and starts gradually brightening again. In our current time delay analysis we consider these long-term high-amplitude brightness variations showing a maximum in 2004 and a minimum in 2009. In the analysis we also take into account the short-term variations in brightness within each observational season.

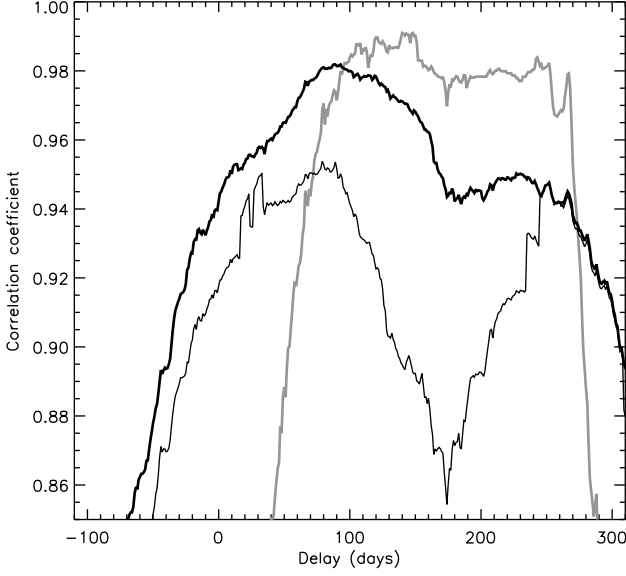
The time delay is measured with the modified cross-correlation function (MCCF) method (see Oknyanskij 1993). The method, its application and test performance for analysis of time series containing large annual gaps are described in Paper I. Here, we briefly outline the approach. In the MCCF method, each data point from the B light curve,  $B(t_i)$ , forms a pair with an interpolated point from the A light curve,  $A(t_i + \tau)$  at time  $t_i + \tau$ , where  $\tau$  is the time lag. The pairs of data points for which  $\tau - \Delta t \leq \Delta t_{ij} < \tau + \Delta t$  (where  $\Delta t_{ij} = |t_j - t_i|$  is the time shift between the  $t_i$  point of the A light curve and the  $t_j$  point of the B light curve) are then used to calculate the cross-correlation function. The interpolation interval  $\Delta t$  is usually chosen as a compromise between the desire to decrease the interpolation errors and to find a sufficient number of data pairs to reliably calculate the correlation coefficient for a given time lag.

For the analysis of the light curves presented in Paper I the value of  $\Delta t$  was adopted to be 90 days under the assumption that quasar UM673 is a slow variable source. This was the smallest value of  $\Delta t$  that we could choose given the large annual gaps in the light curves. The timescale of the short-term variations is comparable, or sometimes, shorter than the interpolation interval of 90 days. In this case the MCCF method does not allow for taking into account variations which are shorter than 90 days, it becomes less sensitive to the short-term variations. In addition,

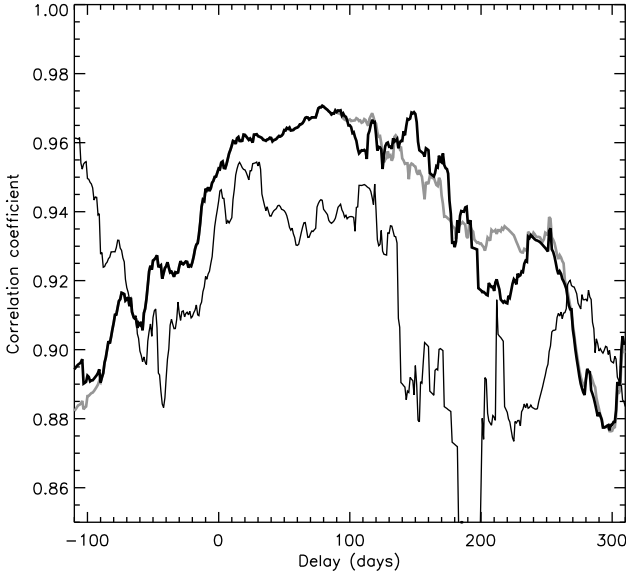
interpolation errors produced for large values of  $\Delta t$  can lead to an erroneous time delay estimate.

In this work, in order to account for the short-term brightness changes and minimize the errors, we use two interpolation intervals,  $\Delta t_{\max}$  and  $\Delta t_{\min}$ . The interpolation interval  $\Delta t_{\max} = 90$  days is the same interval adopted for calculations of the CCF in Paper I. The interpolation interval  $\Delta t_{\min}$  is introduced to take into account the short-term quasar variations within each observational season. It is used to calculate the cross-correlation function for those data pairs for which both data points in the pair (the real point from the B light curve and the interpolated one from the A light curve) are within the same observational season. When the data points do not lie within the same season of observations,  $\Delta t_{\max}$  is used instead of  $\Delta t_{\min}$ . This approach is applied to calculate the cross-correlation function between the time-shifted interpolated A light curve and the discrete B light curve. The time lag  $\tau$  ranges from -500 to 500 days with a step of 1 day. A value of 10 days chosen for  $\Delta t_{\min}$  is comparable to the average sampling of the light curves within one observational season. The origin of high-amplitude rapid brightness changes observed in image B in January, 2010 is unclear. It can be either intrinsic to the quasar with the counterpart in image A which was not observed, or unique for image B. To avoid influence of the data points corresponding to this event on correlation between the A and B light curves, they were excluded from the time delay analysis.

The resulting CCFs for the R, V and I-band data are shown in Figs. 4 and 5. The CCF calculated between the better-sampled R-band light curves (shown by a thick black line in Fig. 4) reaches its maximum at a delay of 88 days with a correlation coefficient of 0.981. For the comparison we plot the CCF calculated between the R-band light curves with the data points corresponding to the high-amplitude event in image B included (shown by a thin black line in Fig. 4). As can be seen, this CCF also reaches



**Fig. 4.** CCFs calculated between the R-band light curves of images A and B with the data points corresponding to the high-amplitude event in image B excluded (shown by a thick black line); and the data points corresponding to the high-amplitude event in image B included (shown by a thin black line). The CCF calculated between the R-band light curves corresponding to the 2003 – 2005 period is shown by a thick grey line.



**Fig. 5.** CCFs calculated between the V (thick black line) and I-band (thin black line) light curves of the A and B images. Thick grey line shows the V-band CCF calculated for the value of  $\Delta t_{\max} = 110$  days.

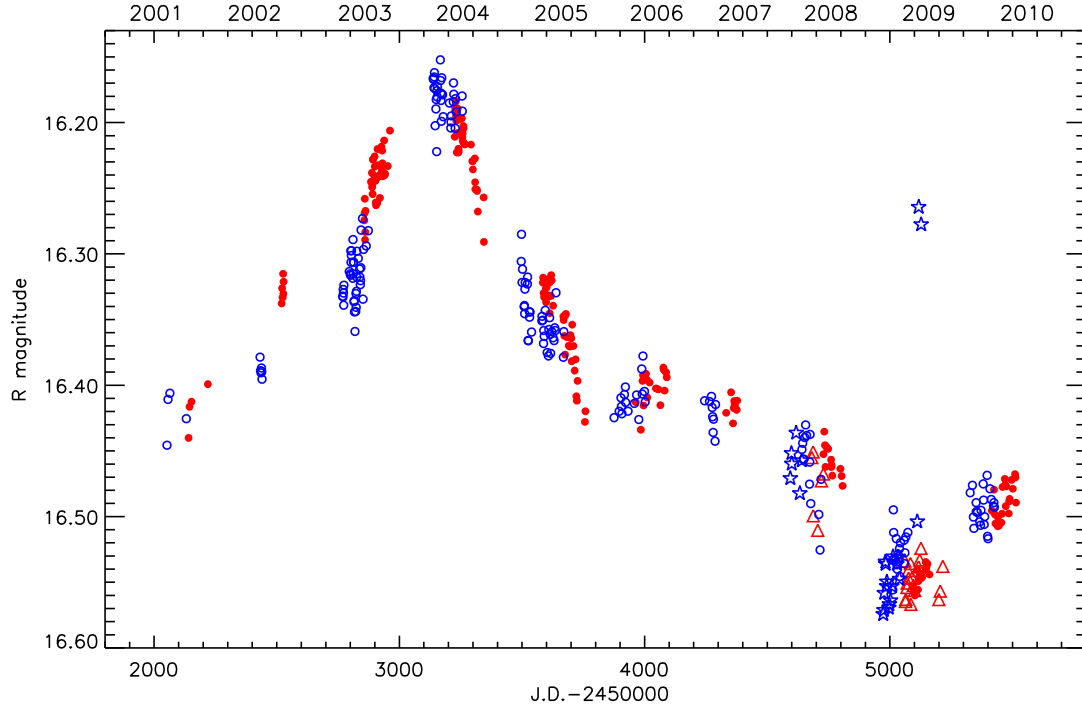
its maximum at a delay of about 88 days but with lower correlation coefficients. It is not as smooth as the first CCF and has secondary peaks at short delays. We interpret these short-delay peaks as originating from the high-amplitude event in image B. The grey thick line in Fig. 4 shows the CCF calculated between segments of the R-band light curves which include only the data points collected between 2003 and 2005. The same observational

data have been used to measure the time delay between the images of UM673 in Paper I. The corresponding CCF has different shape and reaches its maximum at a very different delay of 142 days. The most probable reason for the disagreement in the results is that the single parabola-shape long-term brightness variation observed between 2003 and 2005 can not reliably constrain the delay. The broad peak of this CCF falls in the range of time delays for which the A and B light curves do not overlap each other. We find that in order to measure the delay which is longer or comparable to observational seasons, it is important to analyze more features in the global behavior of the light curves, rather than one single event. Altogether, the long-term brightness changes provide a better constrain on the time delay.

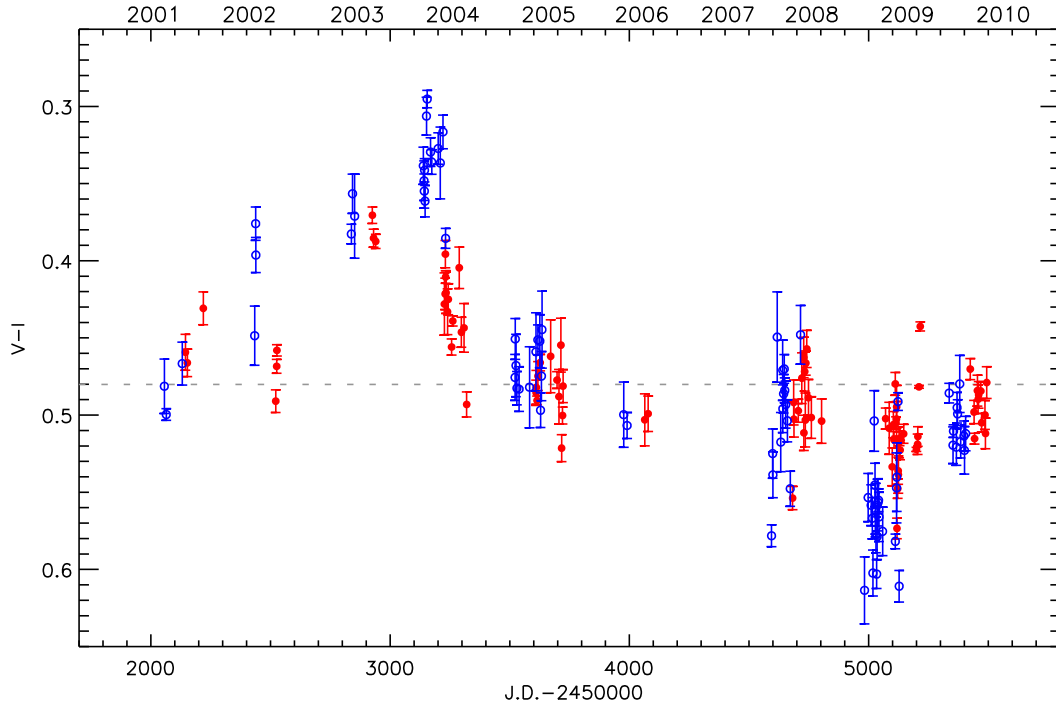
As can be seen in Fig. 5, the shapes of the V and I-band CCFs are different from the shape of the R-band CCF (especially for the I-band light curves). The CCF calculated between the V-band light curves reaches its maximum at a delay of 79 days. The V-band CCF has several secondary peaks on the top of the main peak. The secondary peaks at longer delays disappear with the increase of the interpolation interval. This is demonstrated with the CCF calculated for the value of  $\Delta t_{\max} = 110$  days (shown by a thick grey line in Fig. 5). Therefore, we conclude that these secondary peaks are most probably artifacts caused by the errors in calculation of the CCF at longer time lags. For these lags the number of data pair contributing to the calculation of CCF is small, therefore the accuracy of the CCF is low. The other features of the V-band CCF corresponding to the more prominent central peak remain unchanged. The I-band CCF reaches its maximum at a very different time lag of about 20 days, although it also has secondary peaks at longer delays. Apparently, the poorly sampled I-band light curves with smaller amplitudes of the brightness changes can not accurately constrain delays which are longer than duration of the observational seasons in the I band. As a result, the MCCF method can not find enough data pairs to reliably calculate the CCF at delays longer than 20 days. This leads to a decrease of the I-band CCF at longer delays.

From the cross-correlation analysis we find that the V and R-band CCFs give consistent time delays, although slightly different. As the R-band light curves are better sampled and the R-band time delay corresponds to a higher value of the correlation coefficient than the V-band delay, we consider the R-band value of the delay as a more robust measurement. The light curves of the UM673 images corrected for the time delay of 88 days and the magnitude offset of 2.12 mag are shown in Fig. 6. For ease of presentation the errorbars in the A and B light curves are not shown. We find a good match in the global behavior of the light curves. There is also an overlap of about two months between the light curves for most of the observational seasons.

Uncertainties in time delay measurement due to photometric errors and systematic sampling effects are investigated with the Monte Carlo simulations. We perform simulations of 1000 artificial light curves using Timmer & Koenig’s algorithm (1995) (these simulations are discussed in detail in Paper I). The distribution of the time delays recovered from cross-correlation analysis of the Monte Carlo simulated R-band light curves of images A and B, shifted by the input time delay of 88 days, is shown in Fig. 7. From this distribution we find the mean time delay and its error of  $89 \pm 11$  days (marked by a dotted line in Fig. 7). The most probable value of the delay that can be measured from light curves with similar statistical properties and variability pattern as the observed R-band light curves is  $95^{+5}_{-16} +^{+14}_{-29}$  days (68 and 95 % confidence intervals).



**Fig. 6.** R-band light curves of image A (filled circles) and image B shifted by a time delay of 88 days with a magnitude offset of  $-2.12$  mag (open circles).

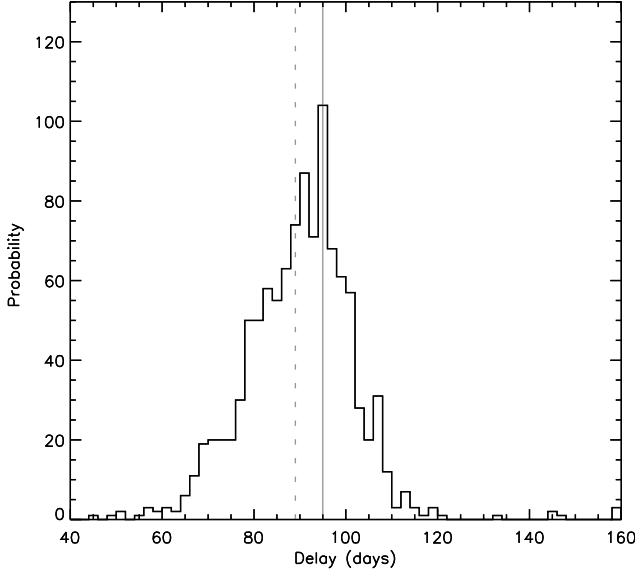


**Fig. 8.**  $V - I$  color curves of images A (filled circles) and B (open circles) of UM673. The color curve of image B is shifted by a time delay of 88 days and a magnitude offset of  $-0.326$  mag. The dotted line traces the average color of the quasar.

## 5. Color variations and evolution of flux ratio

In this section we analyze color variations and evolution of the flux ratio of the UM673 images over more than ten years. The  $V - I$  color light curves of the A and B images of UM673 between August 2001 and November 2010 are shown in Fig. 8. The color

changes are expected to be similar in both images separated by the time delay. In Fig. 8 the image B light curve is shifted by the time delay of 88 days and corrected for the  $V - I$  color difference between images A and B of about 0.326 mag. The combined light curve represents the  $V - I$  color variations of the quasar in the period from 2001 to 2010. As can be seen in Figs. 6 and

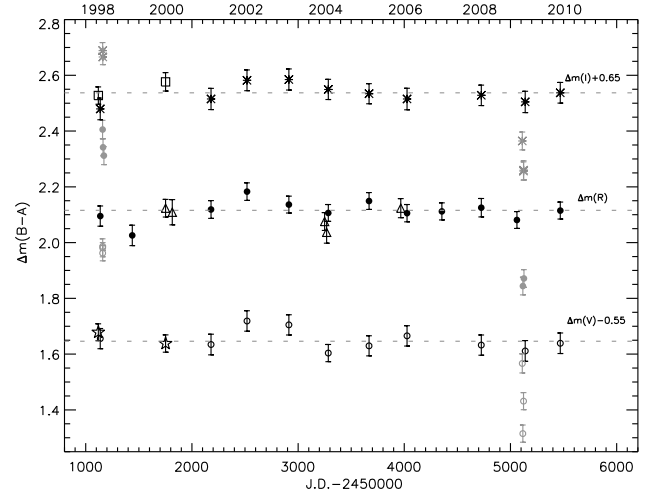


**Fig. 7.** Distribution of peaks of the CCF obtained for 1000 Monte Carlo realizations of the R-band light curves. The peak of the distribution is marked by a solid grey line. The dotted line corresponds to the mean value of the delay.

8, the color variations are well correlated with the brightness variations of the quasar. Similar to the brightness changes, the color curve also shows global maximum and minimum in 2004 and 2009, respectively. From the brightness and color variations of the quasar we see that the image B light curve recorded the brightest state of the quasar. During maximum of the brightness, the quasar was bluer than on average and during minimum of the brightness the quasar was redder than on average. The overall change in the  $V - I$  color index is about 0.3 mag. The overall change the brightness is more than 0.4 mag in the V band. The correlation between color and brightness variations of the quasar is in agreement with numerous observations which show that quasars are generally bluer-when-brighter (see, e.g., Trèvese et al. 2001; Wilhite et al. 2005).

We also analyze the archive Maidanak images of UM673 taken in the V, R and I bands in November, 1998. These image frames have small field of view and do not contain any bright stars except the lensed system UM673. Analysis of these data gives only the relative magnitudes of images A and B of UM673 in the V, R and I bands. We use these measurements of the relative fluxes to estimate the difference between the  $V - I$  color indices of the images in 1998, calculated as  $\Delta(V - I)_{BA} = \Delta m_{BA}^V - \Delta m_{BA}^I$ . The measured color difference  $\Delta(V - I)_{BA}$  for November, 1998 is  $0.373 \pm 0.014$  mag. We find that it is in close agreement with the mean color difference between the UM673 images measured based on the 2001 - 2010 data. Therefore, the color difference between the quasar images is the same on average over more than ten years. This can be considered as an evidence that there were no noticeable microlensing variations in the images of UM673.

In addition, we analyze the differences in magnitude (flux ratios) between images A and B in the V, R and I bands at different epochs. The relation between the magnitude difference and flux ratio is given by  $\Delta m(B - A) = 2.512 * \lg(F_A/F_B)$ . For the analysis we use the following data: images of UM673 taken with the EMMI camera of the ESO New Technology Telescope in



**Fig. 9.** Differences in the V, R and I-band magnitudes between images A and B of UM673 for the 1998 – 2010 period. The measurements based on the ESO archive data are indicated by open stars, open triangles and open squares for the V, R and I bands, respectively. The Maidanak-CTIO magnitude differences are shown by open circles, filled circles and stars. The mean V, R and I-band magnitude differences are shown by dotted lines.

1998<sup>2</sup>; images obtained with FORS1 at the ESO Very Large Telescope in 2000<sup>3</sup>, 2004<sup>4</sup> and 2006<sup>5</sup>; archive Maidanak data collected during the 1998 and 1999 seasons and more recently, between 2001 and 2010 (see Table 1). Note that the ESO data used in the analysis were obtained in the same Bessel system of filters as the Maidanak data. Fig. 9 shows the flux ratios between images A and B over 12 years. The flux ratios measured using the ESO images for the V, R and I-band data are marked by open stars, open triangles and open squares, respectively. The Maidanak flux ratios for the V, R and I-band data are indicated by open circles, filled circles and stars, respectively. The R-band Maidanak flux ratio measured between 2003 and 2010 is corrected for the time delay of 88 days. The rest of the data is too sparse or taken only at a single epoch to calculate time-delay corrected flux ratios. The Maidanak-CTIO flux ratios which are not corrected for the time delay are estimated as average flux ratios for each observational season. The ESO flux ratios are measured based on single-epoch observations. The flux ratio errors are estimated as follows. From the A and B light curves, rms amplitudes of the quasar variability for each season of observations are in the range of  $0.010 \leq \sigma_{var}^R \leq 0.031$  mag in the R band. In order to account for possible changes in the quasar brightness on timescales of 88 days we add  $\sigma_{var}^R \approx 0.031$  in quadrature to weighted average errors measured for each of the observational seasons (see also Shalyapin et al. 2009).

We estimate that the flux ratios were  $\Delta m^V = 2.19$ ,  $\Delta m^R = 2.11$  and  $\Delta m^I = 2.03$  mag for the ESO VLT observations in July, 2000. They roughly agree with the Maidanak V, R and I-band flux ratios of the quasar images in 1998 and 1999. The magnitude differences for the earlier HST/WFPC2 data obtained in 1994 (see Keeton et al. 1998) are  $\Delta m^{F555W} = 2.24$ ,

<sup>2</sup> These images were acquired during Engineering programme 1, Proposal No. 59.A-9001(A).

<sup>3</sup> PI/Col J. Hjorth et al. Proposal No. 65.O-0666(C).

<sup>4</sup> PI/Col Meylan et al. Proposal No. 074.A-0563(A).

<sup>5</sup> PI/Col Meylan et al. Proposal No. 077.A-0155(B).



$\Delta m^{F675W} = 2.29$  and  $\Delta m^{F814W} = 2.09$  mag (where the F555W, F675W and F814W HST/WFPC2 bands roughly match the standard Johnson-Cousins V, R and I bands). Note that although the F555W, F675W and F814W HST/WFPC2 filters are relatively good approximations of the standard V, R and I filters, the difference in photometry between these two photometric systems can reach 0.1 mag (Holtzman et al. 1995). The Maidanak V, R, I-band flux ratios measured based on the multiepoch data collected between 1998 and 2010 are  $\Delta m^V = 2.19 \pm 0.04$ ,  $\Delta m^R = 2.12 \pm 0.04$  and  $\Delta m^I = 1.98 \pm 0.04$  mag. The I-band flux ratio of 1.98 mag is in a good agreement with the NIR K and L'-band flux ratios measured by Fadely & Keeton (2011) based on single epoch observations (1.92 and 1.89 mag, respectively).

As can be seen in Fig. 9, the V, R and I-band flux ratios were stable at different epochs. This can be seen better from the R-band flux ratio measurements corrected for the time delay. The stability of the flux ratio in the different bands indicates the absence of microlensing-induced variations in the system. Small deviations of the flux ratio, which is not corrected for the time delay, from its multiepoch mean value can be explained by the variations intrinsic to the quasar.

It seems that the quasar can exhibit high-amplitude variations over short timescales. From analysis of the archive Maidanak data we find evidence of rapid brightness variations in the system between November 13 and December 23, 1998. The V, R, and I-band relative fluxes of the A and B images changed significantly over a very short time. In particular, the weighted average magnitude differences of images between November 13 and November 26, 1998 were  $\Delta m^V = 2.21 \pm 0.04$ ,  $\Delta m^R = 2.07 \pm 0.04$  and  $\Delta m^I = 1.99 \pm 0.04$  mag. However, in the next month (between December 8 and December 23, 1998) the weighted average magnitude differences were already  $\Delta m^V = 2.53 \pm 0.04$ ,  $\Delta m^R = 2.27 \pm 0.04$  and  $\Delta m^I = 2.05 \pm 0.04$  mag. These measurements are shown by grey symbols in Fig. 9. The increase in magnitude difference  $\Delta m(B - A)$  (of about 0.3 mag in the V band) might indicate significant brightening of image A or simultaneous fading of image B and brightening of image A in December, 1998. The R-band magnitude difference measured from data obtained in September 1999, showed that it returned to the value of November 1998:  $\Delta m^R = 2.03 \pm 0.04$  mag. The magnitude difference calculated for this event shows a clear dependence on the wavelength. The change of the V-band flux ratio is more prominent than that of the I-band flux ratio. Nakos et al. (2005) published photometric results for nearly the same epoch of observations. During the time interval covered by the observations, the A and B light curves of UM673 showed the presence of rapid short-term variations in both images (see Figs. 3 and 4 in Nakos et al. 2005). These rapid variations could alter single epoch flux ratio during a very short time. The same brightness variations should be observed in image B after the 88 day time delay. However this cannot be confirmed due to the lack of observational data for this period.

The high-amplitude brightness variation observed in image B in January, 2010 does not have its counterpart in image A. Taking into account the time delay of 88 days, it should be seen in the A light curve in the beginning of October, 2009. As we do not observe the same brightness variation in image A, it is most probably not connected with the intrinsic quasar variations. The amplitude of brightness changes during this event is higher in the V band (about 0.39 mag) than in the I band (about 0.31 mag) as expected for the microlensing variations (see Wambsganss & Paczynski 1991). However, microlensing by the stars in the lensing galaxy would take much longer time. We conclude that an

independent confirmation of this event might be needed to find an explanation for its origin.

## 6. Discussion

In this study we present the V, R and I-band light curves of the A and B images of the lensed quasar UM673. The light curves cover ten observational seasons, from August, 2001 to November, 2010. We find that both images of UM673 show brightness variations on short (several months) and long (several years) timescales in all three bands. Using cross-correlation analysis of the better-sampled R-band light curves we estimate the mean time delay between images A and B (image A is leading) and its error to be  $89 \pm 11$  days. From the Monte Carlo simulations, the most probable value of the delay that can be measured from light curves with similar statistical properties and variability pattern as the observed R-band light curves is  $95^{+5}_{-16-29}$  days (68 and 95 % confidence intervals). These measurements are based on the observations of much longer time coverage than in Paper I. The time delay of about 150 days measured in Paper I was constrained based on the long-term parabola-shape brightness variation observed between 2003 and 2005. We find that this single event does not allow for correct determination of the time delay. For the revised time delay of 89 days, the global behavior of the A and B light curves matches well. This demonstrates that the observed brightness variations are mainly due to intrinsic variations of the quasar. Analysis of the brightness and color changes does not show evidence of the microlensing variations. The bluer-when-brighter behavior of image A found in the earlier observations of Nakos et al. (2005) is most probably due to the quasar variability rather than due to microlensing.

We find that the flux ratio between the quasar images corrected for the time delay does not evolve with time. Therefore, it is not altered by microlensing which would otherwise causes changes in the flux ratio with time. The measured mean flux ratios  $F_A/F_B$  are 7.6, 7.1 and 6.3 in the V, R and I bands, respectively. The estimated V-band mean flux ratio is in good agreement with the value of Wisotzki et al. (2004). In Wisotzki et al. (2004) the spectrum of image B was rescaled by a factor of 7.78 to match the C IV emission line of image A. Therefore, the estimated emission-line flux ratio between the images is found to be 7.78 at 5780 Å, which roughly corresponds to the effective wavelengths of the V filter. Since there is no microlensing, the difference in the flux ratio in the V, R and I bands is most probably due to extinction in the lensing galaxy (Yonehara et al. 2008).

The measured time delay can be used to estimate the Hubble parameter and constrain the mass model of the lensing galaxy. There are several lens models which predict different time delays between the UM673 images. The predicted time delay for the lens with elliptical symmetry and  $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$  is about 7 weeks (Surdej et al. 1988). Lehár et al. (2000) fitted a set of four standard lens models (SIE, constant M/L models, and those with external shear). The SIE and constant M/L models predict time delay  $h\Delta t = 80$  and  $h\Delta t = 121$  days, respectively. The SIE and constant M/L models with external shear predict time delay  $h\Delta t = 84 - 87$  and  $h\Delta t = 115$  days, respectively. Given that  $\Delta t = 89$  days, the Hubble constant  $H_0^{\text{meas}}$  estimated for the SIE and M/L models is 90 and 136  $\text{km s}^{-1} \text{ Mpc}^{-1}$ , respectively. For the SIE and M/L models with shear it is 94 and 129  $\text{km s}^{-1} \text{ Mpc}^{-1}$ , respectively. These values of the Hubble constant are higher than the Hubble key project result of  $72 \pm 8 \text{ km s}^{-1} \text{ Mpc}^{-1}$  (Freedman

et al. 2001) or improved result of  $74.2 \pm 3.6 \text{ km s}^{-1} \text{ Mpc}^{-1}$  (Riess et al. 2009). This might be a result of an additional convergence to the lensing potential from nearby objects or objects on the line of sight to the quasar (see, e.g., Keeton et al. 2000). If we take into account the total external convergence  $k_T$  of the nearby objects observed in the field of view of UM673, the Hubble parameter from the SIS model, corrected as  $H_0 = (1 - k_T)H_0^{\text{meas}}$ , is  $78 \pm 10 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . This value roughly agrees within the errors with the Hubble key project value of the Hubble parameter. However, there still might be an unaccounted convergence produced by objects on the line of sight to the quasar.

Recently, Cooke et al. (2010) reported the discovery of a previously unrecognized DLA system at  $z=1.63$  in the spectrum of image A of UM673. They also found a weak Ly $\alpha$  emission line in the spectrum of image B at the same redshift as the DLA that indicates a star formation rate of 0.2 solar mass per year. The discovery provides evidence of an additional mass, a galaxy which gives rise to the DLA system toward the UM673 quasar.

The accuracy of the Hubble constant from the time delay in UM673 can be improved in the future by analyzing the external convergence produced by the objects in the field of view of UM673 and reducing the error in the time delay measurement. The latter requires coordinated observations of UM673 at different sites over time interval which can provide better overlap between time delay corrected light curves of the quasar images than the Maidanak-CTIO data. UM673 might exhibit rapid brightness variations of more than 0.1 mag on timescales from one to several months. Observations of these rapid brightness variations during coordinated monitoring of the system can help to reduce uncertainty in the time delay down to several per cent.

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